Review of Dark-Matter Axion Experiments

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We review the status of two ongoing large-scale searches for axions which may constitute the dark matter of our Milky Way halo. The experiments are based on the microwave cavity technique proposed by Sikivie, and marks a 'second-generation' to the original experiments performed by the Rochester-Brookhaven-Fermilab collaboration, and the University of Florida group.

1. INTRODUCTION

Axions, a promising cold dark matter candidate, arise from a minimal extension of the Standard Model to enforce Strong-CP conservation. The Peccei-Quinn solution to the Strong-CP problem in QCD [1] involves an approximate $U_{PQ}(1)$ global symmetry. This $U_{PQ}(1)$ symmetry is spontaneously broken at some unkown symmetry-breaking scale f_a, and the axion is the associated pseudo-Goldstone Boson[2].

The properties of the axion depend mainly on the symmetry breaking scale f_a. Had the $U_{PQ}(1)$ symmetry been exact before the SSB, the axion would be massless. Instead, its mass which is inversely proportional to f_a is given by

$$m_a[eV] \approx 0.6\ eV \frac{10^7\ GeV}{f_a\ [GeV]} \qquad (1)$$

All of the axions couplings are proportional to m_a. The coupling relevant for cavity detectors is the two-photon coupling described by

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha \phi_a}{4\pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} \phi_a \mathbf{E} \cdot \mathbf{B} \qquad (2)$$

where α is the fine structure constant, ϕ_a is the axion field, g_γ is a model-dependent constant of order unity, and $g_{a\gamma\gamma} = (\alpha g_\gamma/\pi f_a)$. For the two most important axion models, KSVZ [3] and DFSZ [4], $g_\gamma \sim 0.97$, and $g_\gamma \sim -0.36$ respectively.

Since f_a is unknown and arbitrary, m_a could have any value. Fortunately, astrophysical and cosmological considerations help constrain m_a. Accelerator-based searches and stellar evolution limits [5] based mainly on SN1987A place an upper limit $m_a < 10^{-2} eV$. Axions created from the vacuum misalignment mechanism [6] would have a cosmological abundance given by:

$$\Omega_a = \frac{\rho_a}{\rho_c} \sim \left(\frac{5\mu eV}{m_a} \right)^{\frac{7}{6}} \qquad (3)$$

where ρ_c is the critical density of the universe. Requiring $\Omega_a < 1$ gives $m_a > 10^{-6} eV$, although this could change in some inflationary scenarios [7]. Combining the two limits gives the allowed mass range, or axion window.

$$10^{-6} < m_a < 10^{-2}\ eV \qquad (4)$$

2. THE MICROWAVE CAVITY AXION DETECTOR

To date, the most efficient method of searching for axions is the microwave cavity technique originally proposed by Sikivie [8]. In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by $hf = m_a c^2 (1 + O(10^{-6}))$. At the lower end of the axion window (4), the frequency of the photons lies in the microwave regime. A high-Q resonant cavity, tuned to the axion mass serves as the detector for the converted photons. The expected signal power varies with the experimental parameters as [8,9]

$$P_{a \to \gamma} \propto B^2 V C Q f \rho_a \qquad (5)$$

where B is the background magnetic field, V is the cavity volume, C is a mode dependent form factor, Q is the loaded quality factor, f is the resonant frequency, and ρ_a is the local halo axion density. Axions couple most strongly to the TM_{010} cavity mode ($C \sim 0.5$), so it is the only mode used in most searches. For the parameters of the U.S. experiment, the power from KSVZ axions is typically $5 \times 10^{-22} W$.

Since the axion mass is unknown, the frequency of the cavity must be tunable. The signal-to-noise ratio (SNR) is related to the integration time t, and signal bandwidth B by Dicke's radiometer equation

$$\frac{S}{N} = \frac{P_{a \to \gamma}}{P_N} \sqrt{Bt} = \frac{P_{a \to \gamma}}{k_B T_s} \sqrt{\frac{t}{B}} \qquad (6)$$

where k_B is Boltzmann's constant, and T_s is the system noise temperature. This expression can be inverted to give the scan rate which scales as

$$\frac{df}{dt} \propto \frac{f_o^2 Q_u C^2 B^4 V^2}{T_s^2} \qquad (7)$$

3. THE U.S. DARK-MATTER AXION SEARCH

This section describes the operations and results of a microwave cavity axion search currently operating at Lawrence Livermore National Laboratory. This experiment, a collaboration of LLNL, MIT, Univ. of Florida, LBNL, UCB, Univ. of Chicago, and FNAL, has been operating with greater than 90% live time since February 1996 exploring the region from 0.3 to 3.0 GHz (1.2 to 12.4 μeV) at better than KSVZ sensitivity.[10] The experiment draws heavily on the experience gained in two pilot experiments performed in the late 1980's, one by a collaboration of Rochester-Brookhaven-Fermilab (RBF)[11] and a second at the University of Florida (UF).[12]

Figure 1 is a schematic of the U.S. dark-matter axion detector.

3.1. Present Experiment

The magnet employed in this search is a superconducting NbTi solenoid constructed by Wang NMR Inc.[13] It is a low current (224 A), high inductance (533 H) design to maximize field stability, which serves to minimize eddy current heating of the cavity. The operating field at the center of the coil is usually 7.62 T. The coil has remained cold since its arrival in March, 1995, using an average of 60 liters of liquid helium per day.

The microwave cavities are right-circular cylinders constructed from stainless steel and plated with ultra-high purity, oxygen-free copper. Annealing the cavities after plating increases the copper's conductivity.

Two different cavity configurations have been used so far in this experiment. The region from 550 - 810 MHz has been scanned with a single cavity 50 cm in diameter and 1 m long. The resonant frequency of the empty single-cavity is 460 MHz and the unloaded Q is approximately 200000. Recently, a set of four indentical cavities has been operated with the output combined in phase using a Wilkinson power combiner. Each cavity has a 20 cm diameter and is 1 m long. The empty frequency of these cavities is 1.16 GHz, and the unloaded Q is approximately 160000. The four-cavity array will be used to search from 810-2000 MHz.

Power-combining multiple cavities allows the entire magnet volume to be utilized as the frequency of the cavities increases. This is possible because the axion signal is coherent on laboratory scales ($\lambda_D \approx$ 10-100 m).

Moving a combination of metal and dielectric rods, running the full length of the cavities, changes the resonant frequency. These rods can move from the center of the cavity to the wall. The single cavity accommodates two rods, while each of the four cavities has one.

To achieve the required 500 Hz resolution in resonant frequency it is necessary to move the tuning rods in very fine steps. The single cavity was tuned using stepper motors with a resolution of 1.8°/step followed by a gear reduction of 42000:1. The final step size is approximately 600 nm, corresponding to roughly 500 Hz frequency shifts. This mechanical system was not practical for the four-cavity array, so a new piezoelectric based mechanism was implemented. The stepping resolution with this system was better than
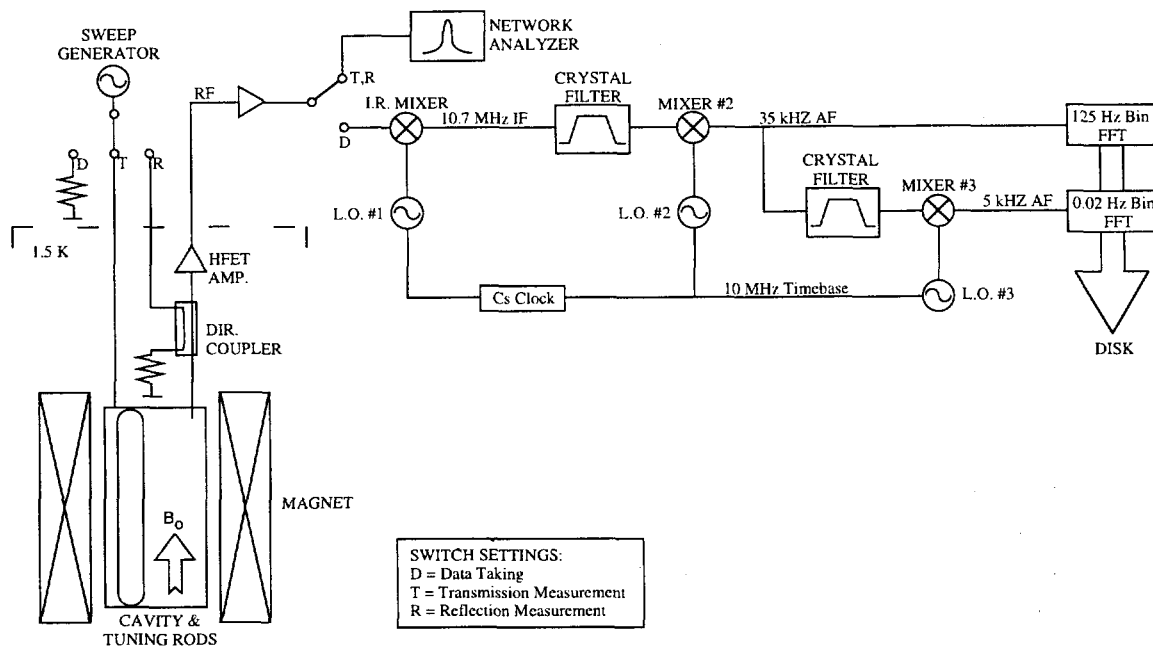
Figure 1. The U.S. Axion search detector.

50 nm, corresponding to a frequency resolution better than 100 Hz. All four cavities must have the same frequency for optimal phase-matching.

Superfluid ^{4}He maintains the physical temperature of the cavities near 1.5 K. A roots blower pumps on a pool of helium in the cavity space, evaporatively cooling the cavities and cryogenic amplifiers to 1.5 K. The pressure of the helium gas in the cavity is roughly 0.1 Torr.

The cryogenic amplifiers used in this search are double-balanced GaAs HFET amplifiers supplied by NRAO.[14] The *in situ* measured noise temperatures range from 1.7 - 4.5 K. For minimum noise temperature, it is important that the amplifiers be positioned so that the B field is parallel to the plane of the HFET channels.[14] Cascading two of these amplifiers achieves sufficient gain (35 dB) to render downstream noise contributions negligible.

Before data is taken at a given frequency, a transmission measurement is made. A fit of the

transmission curve to the sum of a Lorentzian and constant background determines the resonant frequency and Q.

The double-heterodyne receiver shown in Figure (1) mixes a small bandwidth centered on the cavity frequency down to 35 kHz. This audio frequency signal is then sent to medium and high-resolution spectrum analyzers.

The medium-resolution search channel consists of a Stanford Research Systems [15] FFT spectrum analyzer. The sampling interval of the analyzer is 80 msec, giving a frequency resolution of 125 Hz. These data are coadded and the result searched for Maxwellian peaks a few bins wide (about 700 Hz) characteristic of thermalized axions in the halo.[16]

An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal.[17,18] The 35 kHz signal passes through a third mixing stage to shift the center frequency to 5 kHz. A PC based
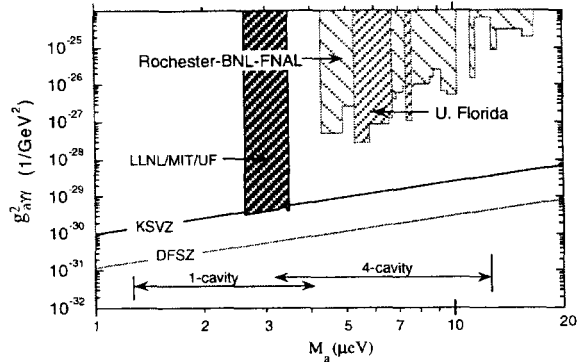
Figure 2. Axion couplings and masses excluded at the 90% confidence level by the U.S. experiments. The solid lines indicate the KSVZ and DFSZ model predictions. The arrows at the bottom indicate the coverage of different cavity configurations. The results from the two pilot experiments are scaled to 90% c.l. and $\rho_a = \rho_{halo}$.

DSP takes a single 50 second spectrum and performs an FFT with 20 mHz frequency resolution, about the limit imposed by the Doppler shift due to the earth's rotation. These data are searched for coincidences between different scans, as well as coincidences with peaks in the medium resolution data.

Positive fluctuations in the power spectrum are identified as candidate peaks and rescanned. Peaks which are statistical in nature will not reappear and can be eliminated as axion signals. Candidates which survive the rescan are considered persistent, and must be checked in other ways. Those few that remained have all been linked to external sources by using an antenna in the room. If a peak were to survive all of these checks, the definitive test would be to see if it appears only when the magnetic field is on.

So far, no axion signal has been detected. Based on these results, we exclude at 90% confidence a KSVZ axion of mass between 2.5 and 3.3 μeV, assuming that thermalized axions comprise a major fraction of our galactic halo ($\rho_a = 450$ MeV/cm^3). This exclusion region and the results from two pilot experiments are shown in Figure 2. For more details see Ref. [21].

In March 2000, the first data from the four-cavity array was taken. This was a commissioning run in a region with a low form factor. With the arrival of new HFET amplifiers in the 1-2 GHz region, production running with the four-cavity array will commence in Fall 2000. The first exclusion limit from a multiple-cavity axion detector is shown in Figure (3).
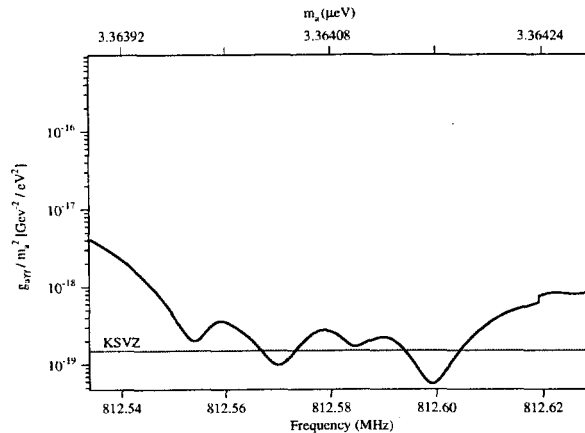
Figure 3. First exclusion plot from the four-cavity array.

4. RESEARCH AND DEVELOPMENT

The ultimate goal of this experiment is to scan as much of the axion window as possible with DFSZ sensitivity. Since the expected power from DFSZ axion conversion is an order of magnitude lower than that from KSVZ axions it would take one hundred times longer to reach similar sensitivity. From Equation 7, the scanning rate goes as T_s^{-2}, therefore, an order of magnitude reduction in system noise temperature would allow a scan at DFSZ sensitivity with the same rate as the present scan with KSVZ sensitivity. This is achievable with new dc SQUID based RF amplifiers.

Predictions of m_a from string models are typically $\mathcal{O}(100\ \mu eV)$, requiring cavities with $f_{010} \sim$

25 GHz. The technique of power-combining signals from many small cavities is only practical for frequencies up to $\approx$ 3 GHz, because the number of cavities required scales as f_{010}^3, where f_{010} is the frequency of the TM_{010} mode. An alternative for reaching higher frequencies is the strategic placement of metal posts inside a single larger cavity.[20]

Work in these two areas is described in the following sections.

4.1. dc SQUID Amplifiers

In the past two years a group at Berkeley led by John Clarke has developed dc SQUID amplifiers in the 100 - 3000 MHz range specifically for the axion experiment. Noise temperatures as low as 50 mK have been measured at a physical temperature of 30 mK.

The dc SQUID consists of two Josephson junctions connected in parallel on a superconducting loop. The SQUID produces an output voltage in response to a small input flux, and is a very sensitive flux-to-voltage transducer. Detailed computer simulations of the signal and noise properties were made by Tesche and Clarke.[22]

The most common configuration of a dc SQUID amplifier is shown in Figure 4.[23] The superconducting loop is a square washer with a slit on one side. The loop is closed via a superconducting counter-electrode connected to the washer by two resistively-shunted Josephson junctions. Flux is coupled into the SQUID through a microstrip input coil separated from the washer by a thin insulating layer. A microstrip resonator is formed by the open-ended stripline whose impedance is determined by the inductance of the input coil and its ground plane, and the capacitance between them. Near the fundamental frequency of the stripline, the gain of the amplifier is strongly enhanced.

The square-washer SQUIDs fabricated at Berkeley had inner and outer dimensions of 0.2 mm x 0.2 mm and 1 mm x 1 mm, and the input coils had a width of 5 μm and lengths ranging from 6 - 71 mm. The resonant frequency of the stripline scales as ℓ^{-1}; the highest frequency amplifier built so had $f > 3$ GHz. Frequencies up to 5-7 GHz should be achievable with the same de-
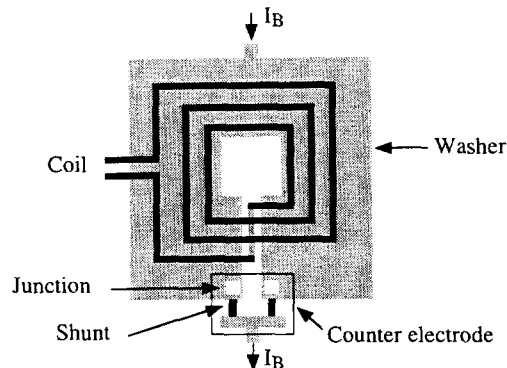

Figure 4. Square-Washer dc SQUID. The signal is coupled to the innermost turn of the coil, the outermost turn is either open-ended, shorted to the washer, or connected to a variable reactance.

sign. Much higher frequencies (up to $\sim$ 25 GHz) may be possible with a new inline-SQUID design.

The bandwidth of these amplifiers have been greatly improved by varying the resonant frequency of the stripline in situ. This has been accomplished by connecting a pair of GaAs varactor diodes across the previously open end of the microstrip.[24] The capacitance of the diodes is controlled by varying their reverse bias voltage. In principle, the tuning range is $0.5f_0 - f_0$, where f_0 is the resonant frequency of the open-ended line, as the load is varied from a short to an open. Measurements of the noise temperature at 4.2 K with and without the varactors revealed no discernible difference.

The noise temperature of the SQUID amplifiers was measured using a heated resistor. The dominant source of noise in these devices is the Johnson noise from the resistive shunts across the Josephson junctions. This noise scales linearly with temperature, so the noise temperature of dc SQUIDs is expected to be proportional to their physical temperature until either the quantum limit $(T_a = h\nu/k_B \ln 2)$[25] is reached or hot electron effects in the shunts become dominant.

In an attempt to reduce the noise temperature, SQUIDs were cooled to 0.4 - 0.5 K in a charcoal-pumped, single-shot ^{3}He cryostat.[26] The system

noise temperature at 438 MHz was 0.50 ± 0.07 K, of which 0.38 ± 0.07 K was contributed by the postamplifier.

At 500 mK, the noise temperatures are already within a factor of four of the quantum limit, which for a 500 MHz amplifier is approximately 35 mK. Demonstrating a quantum limited amplifier will require a much quieter postamplifier. Toward this end, a second SQUID has been used as a postamplifier to the input SQUID. The maximum power gain at 386 MHz was 33.5 ± 1 dB. Noise temperatures below 100 mK have been measured using cascaded SQUIDs cooled in a dilution refrigerator. Work is continuing to demonstrate quantum-limited noise performance.

4.2. Higher Frequency Cavities

A possibility for high frequency cavities with a reasonable volume is the periodic placement of metal posts inside a cavity. Figure (5) shows a triangular lattice of 19 posts inside a circular cavity. With $r/R = 0.1$, this arrangement raises the TM_{010} frequency by a factor of 5 compared to the empty cavity value. The form factor is ≈ 0.5, a reasonable value for a cavity axion detector. It is important to note that the usable volume in this configuration is greater than that of a single empty cavity with the same resonant frequency.
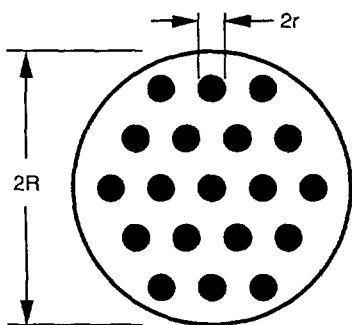

Figure 5. A triangular lattice of 19 posts inside a single circular cavity.

A prototype cavity with 72 posts has been constructed. The posts are arranged as two intertwined square lattices of 36 posts each. One of the lattice is fixed, and the other can be moved as a group. The cavity is tuned by changing the offset of the two lattices. Figure (6) shows the lowest three TM modes for the prototype cavity.
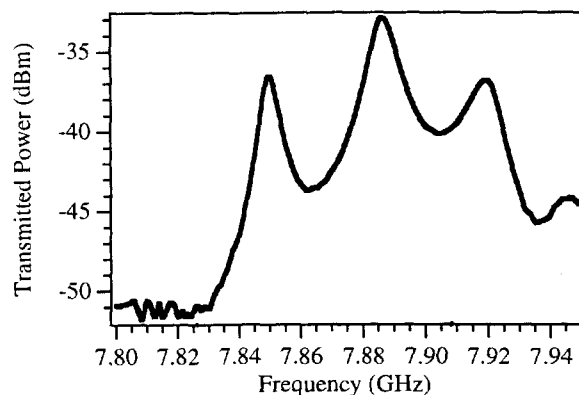

Figure 6. The lowest three TM modes of the prototype multi-post cavity.

More study is required to determine if this is a feasible method to explore higher frequencies. The biggest concerns are limited tuning bandwidth, constraints on the physical dimensions to avoid mode-localization, possible degradation of the form factor as the cavity is tuned, and the density of interfering TE and TEM modes at higher frequencies. Resolving these issues could extend the mass range of microwave cavity axion searches by another decade.

5. RYDBERG ATOM SINGLE-QUANTUM DETECTOR

Another second-generation axion search is under development at the University of Kyoto. This effort seeks to exploit the extremely low-noise photon counting capability of Rydberg atoms in a Sikivie-type microwave cavity experiment. The initial goal is to sweep out a 10% mass window around $2.4\mu eV$.

Rydberg atoms are atoms (usually alkali metals) where one electron is promoted to a principal quantum number $n \gg 1$, near the ionization

limit.[27] The valence electron of such highly excited atoms in hydrogen-like.

An experiment utilizing Rydberg atom single-quantum detection in Kyoto is well along in commissioning ('CARRACK' for Cosmic Axion Research with Rydberg Atoms in a Resonant Cavity in Kyoto).[28] A sketch of the apparatus is shown in Figure 7. The microwave resonator is a single copper cavity (4.5 cm radius, 72.5 cm long) which fits inside a superconducting solenoid (15 cm diameter, 50 cm long, 7 T peak field). Power from the conversion cavity is coupled to a niobium superconducting cavity just above it, where the magnetic field is canceled by a bucking coil. The frequency of both cavities are made to track by means of 6 mm sapphire rods inserted axially into them. The cavities are cooled to < 15 mK by means of a dilution refrigerator.

A beam of rubidium atoms is accelerated, neutralized and directed vertically through the detection cavity. Just before entering the detection cavity, the atoms are excited to a Rydberg state with principal quantum number near 160, by triple optical excitation with three colinear diode laser beams. In the detection cavity, the Rydberg atoms are then Stark-tuned so an E1 $np \rightarrow (n+2)s$ transition is matched to the cavity frequency. After exiting, the Rydberg atoms are selectively ionized by an electric field (around 0.5 V/cm) and the liberated electron is detected and amplified by an electron multiplier ("Channeltron").

Studies have been performed to confirm that the experiment is sensitive to single blackbody photons in the < 15 mK range. These include verifying the temperature dependence, and the number and velocity of the Rydberg atoms.[29] Several percent of mass range around 2.4 GHz ($\sim 10\mu eV$) has been swept out, but candidate peaks have not been eliminated yet, nor have potential systematic backgrounds been rejected.

6. CONCLUSIONS

Axions are a well-motivated dark-matter candidate, enjoying both a bounded parameter space as well as experiments capable of searching a large portion of that region definitively. Quantum-
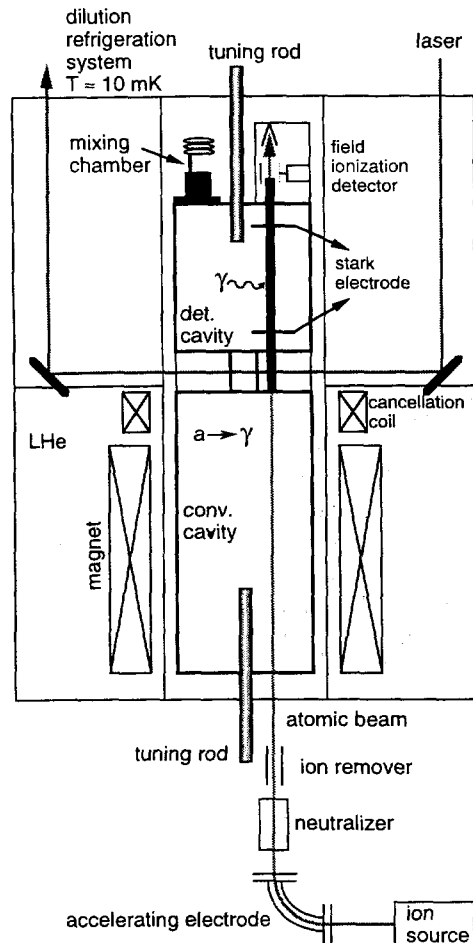

Figure 7. Schematic diagram of the experimental system to search for axions with Rydberg atoms in cooled resonant cavities.

limited SQUID amplifiers and Rydberg atom single-quantum detectors will give microwave-cavity axion detectors sensitivity to the most feebly coupled axion models. At the same time, new high frequency cavity designs may extend the mass coverage by at least another decade.

ACKNOWLEDGMENTS

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